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ESD-TDR-63-171 W-5271

DECISION MAKING UNDER UNCERTAINTY: OVERSHOOTING EFFECTIVENESS IN LARGE SCALE MILITARY SYSTEMS

TECHNICAL DOCUMENTARY REPORT NO. ESD-TDR-63-171

May 1963

P. Fox

Prepared for

DIRECTORATE OF PROGRAMS

ELECTRONIC SYSTEMS DIVISION

AIR FORCE SYSTEMS COMMAND

UNITED STATES AIR FORCE

L. G. Hanscom Field, Bedford, Massachusetts

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ABSTRACT

Theoretical discussion proposing that the minimum expected cost of developing a large scale military system under conditions of uncertainty is achieved by over-shooting effectiveness goals. Implications of the theory in regard to the timing of planning and acquisition are explored and the relationship between the theory and policy is discussed.

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DECISION MAKING UNDER UNCERTAINTY: OVERSHOOTING EFFECTIVENESS IN LARGE SCALE MILITARY SYSTEMS

This paper deals with the allocation of resources to large scale military systems where the planning and acquisition period prior to the operating phase is of several years duration. A characteristic of this type of resource allocation decision, e.g., the acquisition of a major electronic system, is the uncertainty involved in terms of the engineering outcome, the problem of interface with other systems, and the state of the world in which the system must operate. This paper suggests that one means of approaching this uncertainty is to overshoot the effectiveness target relative to what is estimated as the most likely military effectiveness requirement for an assigned mission.[1]

The general theory is developed in the next section. Following that, an analytic solution is presented using a dynamic programming formulation. The theory of overshooting is shown to have implications in terms of the relative timing of research and acquisition, as well as in terms of the number of projects which should be undertaken with a fixed budget. While serious obstacles make the testing of the concepts discussed difficult, there are certain lessons to be learned from the theory itself which can lead to improved policies concerning system choice. These lessons conclude this discussion.

I. GENERAL THEORY

Two salient characteristics of electronic systems are that they take several years to be developed, and that considerable uncertainty surrounds their ultimate effectiveness as well as the future environment in which they will operate. This uncertainty assumes the form of questions as to the performance of planned system components, the degree to which they present coordination problems with other components, enemy posture at the time the system is operational, as well as other military and political considerations. The two major types of uncertainty then are, for our purposes, related to "engineering" or "state of the universe" considerations. In the face of this, the decision maker must select a level of resource allocation in a military system which is required to attain a pre-assigned mission at a set future time. Examples of such a mission might be to identify and report enemy aircraft, notify a Commander of a nuclear event, or to keep the President informed.

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[1]This paper seeks to extend the work of William Marcuse, Strategy for Treating Uncertainty in the Planning and Review of Military System Procurement Programs, The MITRE Corporation, Bedford, Mass., W-4444, 6 November 1961. Certain concepts of William Marcuse are reviewed here without further reference. I also wish to acknowledge the helpful suggestions of James R. Miller, III.

The following assumptions are made, most of which will subsequently be relaxed:

1. The resource allocation under consideration relates to a large scale integrated system which must accomplish a given mission at a fixed date several years hence.

2. The system has three time phases, planning (research), acquisition, and operation. Only the acquisition (procurement and construction) phase is of interest here, and the terminal dates are prescribed by higher authority.

3. There is no military advantage associated with earlier operation of the system, nor with a system which more than accomplishes the predetermined mission.

4. Effectiveness units are somehow measurable and thus provide a unidimensional numeraire or standard.

5. The function of the decision maker in this context is to minimize the expected cost of acquisition associated with achieving the given mission.

The thesis of this paper is the net expected cost[2] may be minimized by overshooting relative to the estimated required effectiveness level. It is assumed for the time being that the decision refers to two time periods and that there exists a symmetric probability function which defines the likelihood viewed from period one, that any given number of effectiveness units will be necessary in period two.[3] In other words, the decision maker selects a programmed effectiveness level in this period and in the next period finds out how accurate his judgment was. He can err in either of two directions. He can overbuild[4] the system, or he can allocate insufficiently and face the need to "reprogram" or revise upward his previous acquisition plans. The crux of this paper is that in large scale systems, e.g., electronic ones,

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[2]Net expected cost is defined as the difference between the actual cost and the cost which would have resulted had the required effectiveness level been known in advance with certainty. In the two period analysis which follows, if this level is overestimated relative to actual needs, the net cost is that of overbuilding; if this level is underestimated, it is that of reprogramming upward.

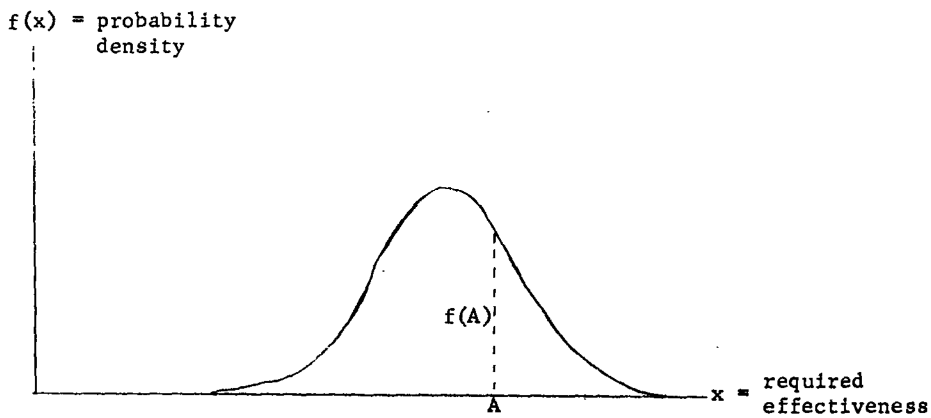
[3]The approach to decisions beyond the two-period horizon is discussed later.

[4]Overbuilding and overshooting are related but differentiable. The following definitions differ slightly from those of W. Marcuse (W-4444, p.9): Overshooting is the ex ante decision to allocate resources to a system in excess of the expected requirement. Overbuilding is the ex post result if a larger than optimal number units, or amount of capacity, is actually procured.

the cost of reprogramming may greatly exceed the cost associated with attaining more than the required level of effectiveness; hence the decision maker should consider overshooting relative to the expected effectiveness requirement.[5] He may minimize the <u>expected</u> cost of overshooting plus the <u>expected</u> cost of reprogramming by allocating at a level which is higher than that believed necessary to just accomplish the mission.

This theory may be examined in terms of a loss function in the two period case (the words "loss" and "cost" are used interchangeably). The decision maker is unable to predict in period one the precise effectiveness required in period two but can attach a probability distribution to the outcomes as illustrated in Figure 1.[6]

<u>Figure 1</u>



<u>Probability Density Function of Effectiveness Required in Period II as Viewed in Period I</u>

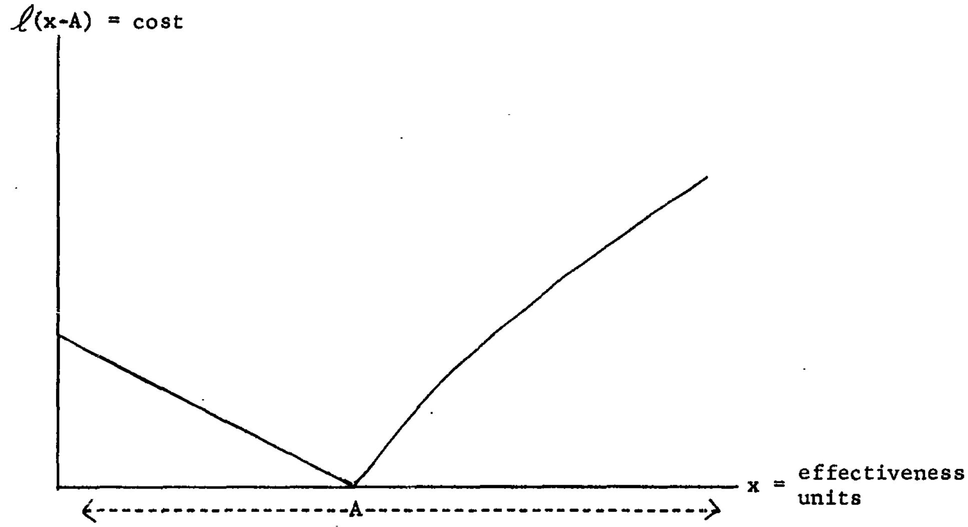
[5] In the multi-period case examined subsequently, it may be desirable to overshoot even if the reprogramming cost does not exceed that of rebuilding, (per unit of effectiveness), for two reasons. First, overshooting may save a number of instances of reprogramming. Second, if effectiveness goals are not overshot, it is possible that an intermediate re-examination during the acquisition stage results in reprogramming upward, even though the final effectiveness requirement may not exceed the initial estimate.

[6] The probability distribution is symmetric in this example. It is suggested that present practice is to set the programmed effectiveness level either at the most likely (mode) or at the expected (mean) value. The symmetric distribution obviates the need to examine which (mode or mean) best describes current policy. It is suspected that in general the probability distributions are skewed to the right, since there is a higher probability of the effectiveness level required being considerably over than considerably under the expected outcome. If this skewness does in fact exist, the case for overshooting is stronger than is presented here.

This distribution defines (in period one) for each x along the abcissa a probability density f(x) that x effectiveness units will be required (in period two) when the system is operational.

The decision maker also has a loss function which describes, if he has overbuilt, the cost in excess of that which he needed to have spent, and if he has allocated insufficient resources, the net cost of reprogramming. He suffers no loss if he has guessed the outcome correctly. For simplicity, it is assumed that the loss is strictly a function of the difference between the stochastic effectiveness requirement, x, and the programmed level of effectiveness, A, and is independent of the absolute levels of x and A. A loss function $\ell(x-A)$ is shown in Figure 2.

Figure 2



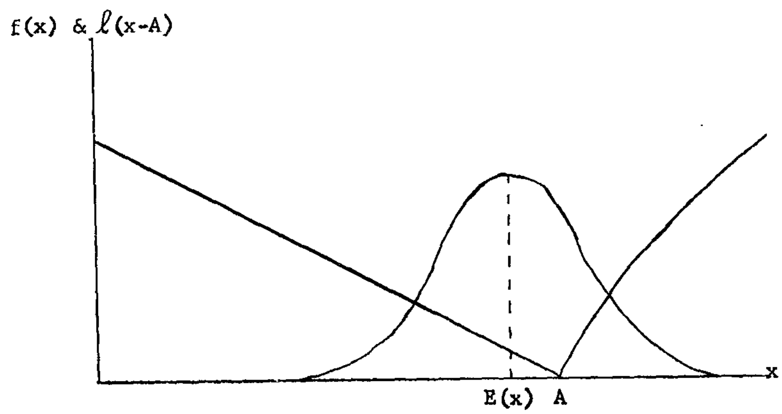
Conditional Loss Function for Overbuilding and Reprogramming

If the decision maker guesses the outcome correctly he suffers no loss, and is at A. If he overbuilds he is to the left of A and suffers a loss as indicated by the functional relationship because he has spent more than was necessary to develop his system. If he fails to develop sufficient effectiveness and is therefore to the right of A, he must redo some of the engineering and design, add more components or otherwise reprogram. This may involve a higher cost than that of overbuilding. In the extreme case the cost of extensive reprogramming may be such as to make it cheaper to rebuild the system entirely.

Equipped with the loss and probability functions, the decision maker is in a position to minimize his total expected loss. This is calculated by multiplying the different losses by the probability of suffering that loss, and summing the resulting products. The probability function is given and different program levels are examined to see which one results in the least expected cost. This corresponds to superimposing the loss on the probability function such that expected loss is minimized. For continuous functions, the expression for the expected total cost is

$\int_0^\infty f(x) \; \ell(x-A) \; dx$, where $\ell(x-A)$ is the loss function and $f(x)$ is the probability function. The loss $\ell(x-A)$ is multiplied by the probability of suffering that loss, $f(x)$, and the conditional losses are summed up or integrated over the range of the probability function. The expression for the expected total cost is minimized through the usual methods of taking the derivative with respect to x and equating the resulting function to zero. Given a symmetric probability distribution, if the cost of reprogramming per unit of effectiveness exceeds that of overbuilding, the minimum cost A will occur at a value greater than the mean, E (x), of the probability distribution (i.e., to its right along the abcissa), as in Figure 3.

Figure 3

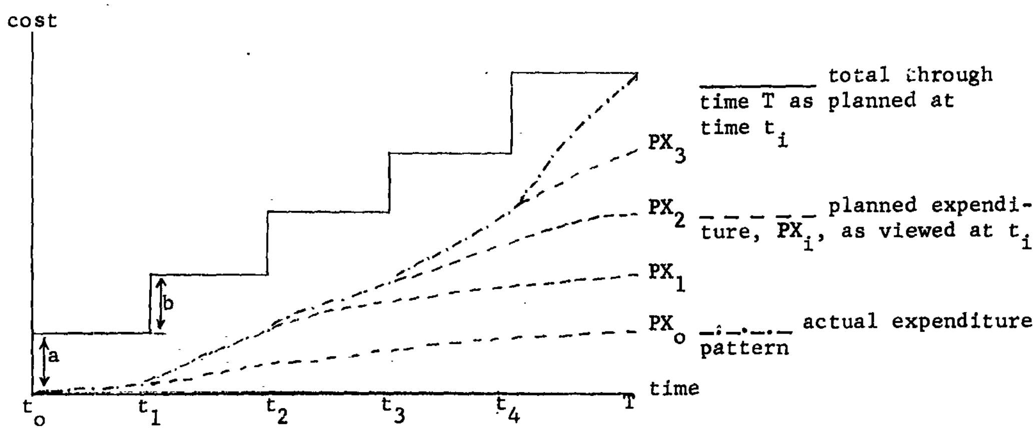


Balancing the Expected Costs of Overbuilding and Reprogramming

The general answer is the same in the multi-period case to which the reader's attention is now directed; given loss curves and probability distribution as above, cost is minimized by overshooting the expected required effectiveness. While it may not be possible in practice to obtain the functional relationships, the direction and nature of an improved policy is apparent.

It may be instructive to assume that the planned effectiveness requirement increases monotonically in discrete jumps (at periodic re-examinations) and that the expense in building the completed system is well in excess of that originally planned. Present budgeting methods can be traced (see Figure 4).

Figure 4

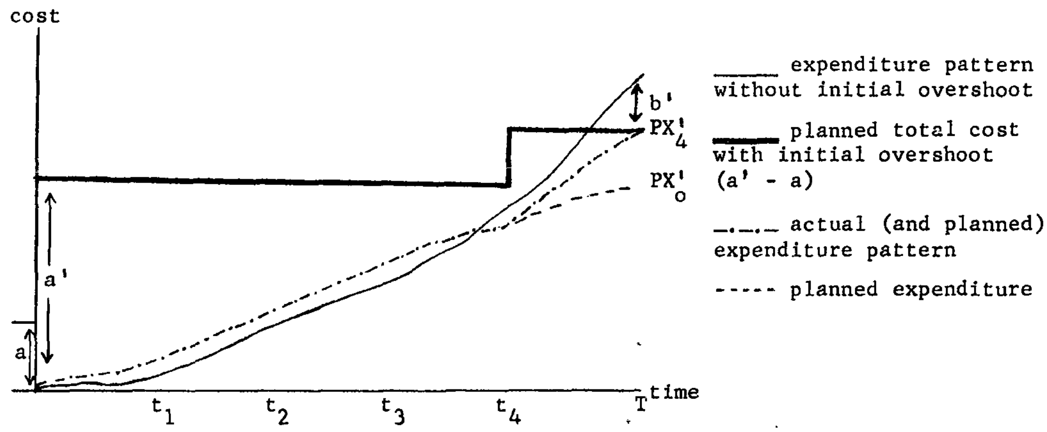


Expenditure Pattern under Present Policy -- Estimated Required Effectiveness Increasing with Time

At time t_o, a units of effectiveness are determined to be the most likely requirement at time T. At time t_1 the program is reviewed and it is determined that an additional b units are required, and so on until t_4 when an accurate appraisal is finally made. What spending pattern is indicated by this? The decision maker plans for a units and establishes a cumulative planned expenditure curve, PX_o. The planned expenditure as viewed at t_o and the actual are identical until t_1 when the program is reconsidered. Since a higher level of expenditure is called for at that time, a new spending plan PX_1 is developed based on the new estimate, and again the new planned and actual are identical between t_1 and t_2. This pattern is followed until the completion date T when the system is in operation.

We now want to examine the path expected under the overshooting policy (see Figure 5).

Figure 5



Expenditure Pattern Under Overshooting Policy -- Estimated Required Effectiveness Increasing with Time

The estimate at period t of the final effectiveness requirement is a, the same as before. However, instead of planning expenditure to achieve effectiveness a, we select some new level a', with a' > a. Based on a', a planned expenditure rate PX_0' is established, and followed until t_4, rather than until t_1 as before. At t_4, additional investment is deemed necessary, but because of the initial overshoot, an amount b' is saved by virtue of fewer instances of reprogramming. It is also conceivable that the initial overshoot, (a' - a), results in overbuilding and the cost of meeting effectiveness requirements is considerably higher than if an overshooting policy were not pursued.

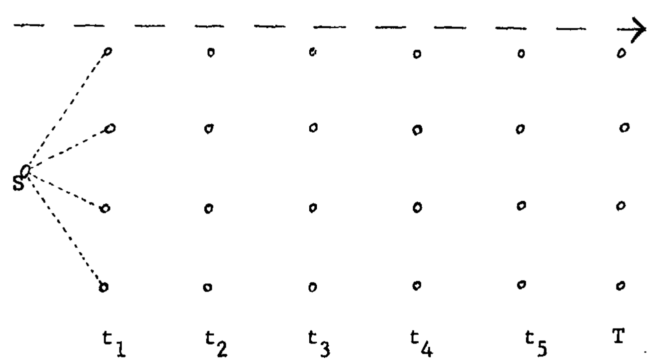
II. AN ANALYTIC SOLUTION

Before delving too deeply into mathematical terminology, it may be revealing to examine, in a relatively non-quantitative manner, the principle underlying the analytic solution.

1. The Principle Underlying the Dynamic Programming Approach

Intuitively one might conceive of the problem at hand as being that of selecting the path involving minimum expense from one end to the other of a grid where each column of "nodes", designated by circles, denotes a point in time, and within each column the individual node represents possible states for the programmed effectiveness and estimated effectiveness requirements. Let us assume that the decision maker is constructing his system over five time periods and that there are four states that the program or estimate can be in at any one time (see Figure 6).

Figure 6



Grid Showing Possible Program and Estimate States through Time

The estimates of system needs as well as the program itself traverse the grid from S to T, the start of the program to the end. At each succeeding time period both the program and the estimate are at particular nodes or states. There are costs and rewards attached to moving the program up and down the column of nodes. The decision maker wants to go from S to T across the grid at minimum cost. At each period he can re-estimate system needs and can reprogram upward or downward at a known cost. He also knows the state of the program at that time, the probability, given his revised estimate, of any particular node being the estimate in the following period, as well as the cost of adjusting the program in that period to any node. The decision maker's policy consists in establishing a program for each period at a node such that he minimizes the expected cost of building the system.

He does this using the technique of dynamic programming. This involves first establishing an optimal policy from the penultimate period, T-1, to the last period, T; then, using this information proceeding from period T-2 to period T, and so on, successively working backwards, one period at a time to the initial decision point. The next to last period in this example is t_5. Because the world is uncertain, both his program and estimate may be at any of the four nodes. He must therefore develop a policy, given program and estimate states at any combination of nodes at t_5, as to the level at which he would establish his new program using the information described above. His calculations yield both the best policy, given that he is at a particular combination of states, and what he expects that policy to cost. Having developed this information for t_5 (and not before) he is able to answer the same questions for t_4. He knows the cost of adjusting his program at that time, the probability of transformation from each estimate in t_4 to any estimate at t_5, and on the previous iteration he has already calculated the expected cost of being at any combination of program and estimate states in t_5. Thus he establishes the best policy through time T, with its expected cost, given a program and estimate at any combination of nodes at t_4. Now, and only now, may he develop this information for t_3, and so on back to the start of the program. These calculations produce an optimal policy for each t_i, in particular for the current period, t_1, as well as the expected costs associated with it. If the program state chosen for the first period exceeds the estimate state, this may be described as a policy of overshooting.

2. <u>The Dynamic Programming Solution</u>[7]

This section sets forth an analytic, normative solution which defines the optimal program over several time periods using a dynamic program formulation. The reprogramming decision is made at discrete intervals and the probability distribution is discrete. This does not change the solution since the time and probability intervals can be made small.

Let T be the final time period. There are two relevant state variables,

1. π_j^{t-1} = program at jth state at the start of time t, measured in effectiveness units as of T. The new program determined in period t is π_ℓ^t.

2. E_i^t = estimate at ith state of final effectiveness requirements at T as viewed at time t.

[7] The more casual reader may wish to omit this section; the Mathematics are a quantification of the theory already presented.

For each period t there is available an E_i^t and a π_j^{t-1}, the states of the estimate and program respectively.

The dynamic programming solution may be expressed equivalently using equations or matrices. We begin with the equation formulation and solve recursively starting from period T-1 to the start of the program. This involves defining the following variables:

p_{ik}^t, the probability transformation from E_i^t to E_k^{t+1}. p_{ik}^t is the probability of an estimate E_k^{t+1}, given an estimate E_i^t. Thus, for each E_i^t there is defined a probability transformation to each E_k^{t+1}; $\sum_k p_{ik}^t = 1$.

$r_{k\ell}^t$, the expected cost of entering period t with an estimate E_k^t and a program π_ℓ^{t-1}. In the final time period, $r_{k\ell}^T$ is the cost of having overbuilt the system under consideration for $\pi_\ell^T > E_k^T$; for $E_k^T > \pi_\ell^T$ it is the cost of reprogramming at time T from π_ℓ^{T-1} to π_k^T. In the last period, the program after adjustment can not be less than the estimate E_k^T.

$m_{j\ell}^t$, the cost of reprogramming from π_j^{t-1} to π_ℓ^t.

The following inputs are required:

p_{ik}^t for all i, k and t

$r_{k\ell}^t$ for all k and ℓ, for T only

$m_{j\ell}^t$ for all j, ℓ and t.

The general solution of the dynamic programming problem is given by

$$r_{ij}^t = \min_{\ell} \left[\sum_k \left(p_{ik}^t\right) \left(r_{k\ell}^{t+1}\right) + \left(m_{j\ell}^t\right) \right]$$

In the next to last period, the optimal policy involves adjusting from π_j^{t-1} to π_ℓ^t where the appropriate π_ℓ^t is given by solving equation (1) for t = T-1. At time T-1, the program and estimate are π_j^{T-2} and E_i^{T-1}. Adjustment to each conceivable π_ℓ^{T-1} is examined and since the state of the program and estimate are not known beforehand, a policy must be formulated alternatively for each π_j^{T-2} and each E_i^{T-1}. The expected total cost of leaving T-1 with π_ℓ^{T-1} is the cost of adjusting the program from state j to state ℓ in this time period, $m_{j\ell}^{T-1}$, plus the expected cost of entering the final time period in state ℓ, $\sum_k \left(p_{ik}^{T-1}\right)\left(r_{k\ell}^{T}\right)$. The expected cost is calculated for each π_ℓ^{T-1} and the minimum over the ℓ's is selected. This minimum is calculated for each combination of π_j^{T-2} and E_i^{T-1}.

The resulting expected minimum costs at T-1 are used as the $r_{k\ell}^{t}$'s for the calculation for T-2 using equation (1) and the dynamic program is solved for that period. The program is in state π_j^{T-3} with E_i^{T-2} and we wish to adjust to a π_ℓ^{T-2} such that net expected costs through T are minimized. p_{ik}^{T-2} is given as is $m_{j\ell}^{T-2}$, the cost of adjusting the program from π_j^{T-3} to π_ℓ^{T-2}. For each k and ℓ, the $r_{k\ell}^{T-1}$ has been calculated in the previous period through equation (1). The $r_{k\ell}^{t}$'s and conditional optimal policies are then calculated for T-3 and so on back to the current decision period.

For the corresponding matrix formulation the following matrices are defined:

P^t, a Markov matrix, which has a typical element p_{ik}^{t}, the probability transformation from E_i^t to E_k^{t+1}.

M^t which has a typical element $m_{j\ell}^{t}$, the cost of reprogramming from state j to state ℓ in time period t.

R^t which has a typical element $r_{\ell k}^{t}$ which is the cost of being in state E_k^t, π_ℓ^{t-1} entering period t.

As before, the following inputs are required:

P^t for all i, k and t

R^t for all ℓ and k, for T only

M^t for all j, ℓ and t.

For any matrix, A, with elements a_{ij}, let $A_{.j}$ signify the jth column vector of A, and $A_{i.}$ the ith row vector of A. Then the expected cost associated with being in state E_i^t and any π_j^{t-1} is $R_{.i}^{t} = \min_\ell \left[U(P_{i.}^{t} R^{t+1}) + M^t\right]$ where U is a column vector having the same number of elements as there are states with each element equal to 1. $\left[U(P_{i.}^{t} R^{t+1}) + M^t\right]$ is calculated for each i and yields a square matrix for each i. Minimizing on ℓ corresponds to taking the minimum of each row to form the ith column vector of R^t. As in the equation formulation, the solution is derived recursively starting with period T-1, then proceeding to period T-2, and so on until the current decision period is reached.

III. GENERAL NATURE OF COST AND PROBABILITY FUNCTIONS

While it may not be possible to derive all of the inputs necessary for an empirical analysis, certain hypotheses may be made regarding the relative nature of the probability and cost curves which determine the solution.

1. The Probability Function

As mentioned in Section II, there are two basic sources of uncertainty involved in developing a large scale system, that which relates to "engineering", and that which relates to "state of the world" considerations. In general, that due to the state of the world increases as the time span for the program increases. The extent of overshooting then will increase with the time span. Engineering uncertainty will vary as an inverse function of the degree of experience in constructing that particular type of system.

2. The Cost Function

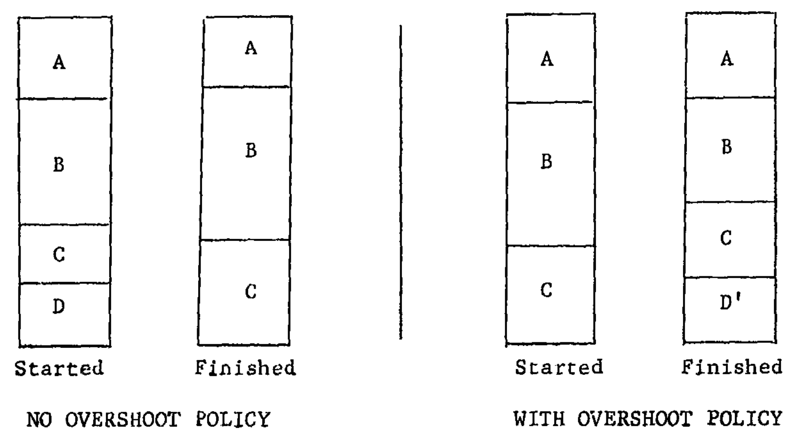
When a system has been overbuilt, the net expected cost is the cost of the actual construction minus that of the system which would just accomplish the pre-assigned mission. When reprogramming is necessary, the net expected cost is the cost of achieving the required effectiveness having initially programmed for less, minus what would have been the cost of programming directly for the correct effectiveness requirement. The cost of upward readjustment (reprogramming) after construction is underway or near completion is a function of system flexibility; the less flexible the system the more it costs to reprogram. Here, a distinction can be made between single and multiple unit systems. A single unit system, consisting of one or at most a few units, is reprogrammed primarily by altering its design thus affecting its capacity, whereas the reprogramming of a multiple unit system which is procured in quantity, as is true of most weapon systems, usually involves changing the number of units to be procured. This model is applicable to both types although one would expect the cost of reprogramming to be higher in the former due to lack of flexibility. Consequently, a higher degree of overshooting relative to the most likely outcome is indicated for single unit systems. While the distinction is often a matter of degree (is a large-scale command and control network with several radars a single or a multiple system?), electronic systems are in general single unit in nature and the expenses of reprogramming, where called for, are high.

Finally, the cost of reprogramming changes with time. As the system nears the completion date, the cost of reprogramming rises because more components need to be redesigned and/or rebuilt. However, the uncertainty decreases as the completion date approaches.

IV. IMPLICATIONS FOR TIMING OF PROJECTS

The theory favoring overshooting of effectiveness goals has two implications as regards the timing of projects under consideration. These refer to the timing of individual projects given a fixed budget, and the relative timing of planning and acquisition. When the decision maker is constrained by a fixed budget, it is implied that fewer projects will be undertaken at the time of adoption of the theory. Assume a fixed budget with ordered preferences for four systems A through D (see Figure 7).

Figure 7



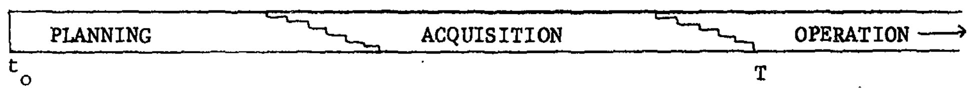
Comparative Number of Projects Undertaken with and without Overshooting Policy

where A is considered to be of greatest importance. If the most likely outcome is used as an estimate, the four projects are started. After a time, owing to the uncertainty involved, some become more expensive and others cheaper. However, the cost of reprogramming is high and in some future time period the low priority project may be dropped. Under the overshooting policy, A, B and C only would be undertaken initially because more investment would be required for these projects to achieve the same goal. However, because of the cost savings realized, it might be possible to pick up another project, D', at a later date (see Figure 7).

[8]The budget is for all intents and purposes fixed at some level of decision making. If it is not fixed for a particular agency or department, it might be fixed for the Federal Government because of political considerations. If not, it is definitely fixed for the country as a whole.

The second implication refers to the relative timing of the planning phase on one hand and the acquisition phase on the other. Let the planning on a given system start at a fixed time, t_o, and the acquisition <u>end</u> at a fixed time T (see Figure 8).

<u>Figure 8</u>



<u>The Three Phases in the Development of a Typical Military System</u>

Because the uncertainty (variance of the probability function) decreases with time, there is a saving which can result merely by postponing the acquisition phase thereby reducing the likelihood of extensive reprogramming. This is traded off against the expense of speeding up the process of acquisition. However, the extent to which the start of the acquisition period should be delayed is less if an overshooting policy is followed because this policy reduces the cost of uncertainty during acquisition. Under certain circumstances it might be possible to conduct research directed toward the reduction of uncertainty since a better ability to predict the state of the world at the time the system becomes operational would reduce the uncertainty and thereby reduce the expected cost.

V. A NOTE ON THE ABILITY TO OVERSHOOT

Hitherto it has been assumed that "effectiveness" is a unidimensional quantity. In practice this is not the case and technological factors may prevent building more effectiveness into the system. On the other hand, tradeoffs among parts of the system may be possible. One might hypothesize a situation where a computer performs functions as part of a command and control network. The decision maker would like to overshoot by having a more rapid machine, but the speed already planned has reached the limit of the state of the art at that time. He may, however, find that increasing memory capacity or input/output speed accomplishes the same purpose in terms of the desired results.

This paper has discussed the concept of overshooting system effectiveness to accomplish a predetermined mission at a fixed future date. The theory is more general than this. A mission is accomplished through one or more systems; each system is composed of subsystems, components and subcomponents. Each part of the system exists for a certain purpose and the overshooting theory holds at each level of analysis. In other words, it may pay to overshoot in designing the sub-components to ensure that the components of which they are a part function as desired, and similarly for the subsystem and the system level. On the other hand, the extent of overshooting which minimizes cost is reduced if deficiencies in one subcomponent may be compensated for by overcapacity in another.

VI. LESSONS FOR THE POLICY MAKER

This paper has presented criteria which should be used to determine the level of resource allocation which minimizes expected costs of a military system designed to accomplish a mission at a specified time in an uncertain world. The analytic solution presented does yield an optimum under the assumptions although the task of determining this optimal program presents difficult problems of data collection. The theory as it stands, however, can lead to an improved policy. Military decision makers should be cognizant of the fact that the optimal program is determined jointly by both the probability and the cost functions, not by the mean or modal effectiveness requirement alone. Because of possible reprogramming costs the optimum will in most cases be at an investment level above both the most likely value and the expected value of the probability function taken alone.

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Hq. ESD, L.G. Hanscom Field, Bedford, Mass.
Rpt. No. ESD-TDR-63-171. DECISION MAKING UNDER UNCERTAINTY: OVERSHOOTING EFFECTIVENESS IN LARGE SCALE MILITARY SYSTEMS. Final report, May 1963, 18p. incl. illus.
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